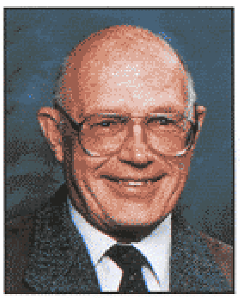
Shaft CenterLINES

Basic rotor-to-stator thermal rubs which exhibit rotative speed (1X) symptom only



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Rubs create the greatest variety of malfunction symptoms of all rotor behavior mechanisms, from chaotic vibration to very well-ordered 1/4X, 1/3X, 1/2X, 1X, 2X, and even ratios such as 1/7X, 2/5X or 4/9X. Furthermore, these ratios may be related to a forcing frequency, which is not necessarily the rotative speed of the machine.

Since the early 1930's (and probably before), steam turbine manufacturers have noted, "When a shaft rub occurs, the rotor rotative speed (1X) phase angle slowly lags and may fall behind a full 360 degrees over many hours." (This was in either a Westinghouse or General Electric operations manual; I think it was the latter). As a result, almost everyone knows this basic rule of thermal rubs. At Westinghouse, it has been referred to as "impaction" of the rotor hitting the stator (which sounds like a dental problem to me).

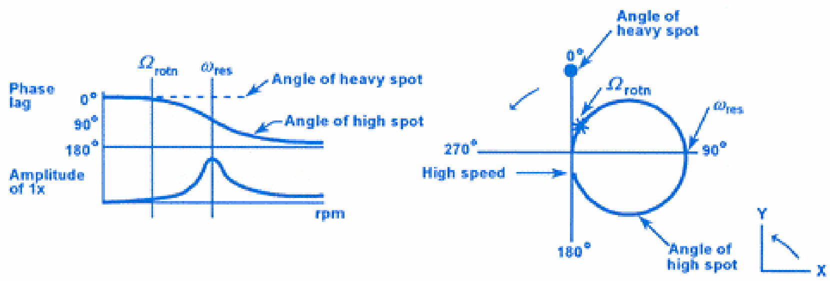

Figure 1

However, several Bently Nevada customers and Bently Nevada's Machinery Diagnostic engineers have clearly documented cases where "what everyone knows" is NOT what always happens. Sometimes the 1X phase LEADS!!

Let's go back to some basics, and then see why a simple thermal rub may exhibit LEADING or LAGGING phase. Figure 1 shows a Bode and polar plot of a very simple rotor system operated well below its first mechanical balance resonance "critical".

At this rotative speed (Ω rotn), suppose that the high spot lags the heavy spot by 3 degrees. Next, suppose that there is some sort of bow, due to unbalance, or a permanent bow. Also, suppose that the shaft material has a positive thermal coefficient of expansion, as with a steel shaft.

Figure 2

Also, suppose that this rotor touches the housing (usually at seals, but wherever) at a place along the shaft, not at its nodal point (Figure 2).

When this "touch" is severe, the rotor bows out at the high spot, as that is the hot spot. The original heavy spot was 3 degrees behind the high spot, but because the rotor direct stiffness increases greatly due to the rub, the system mechanical resonance increases, and the 3 degree lag temporarily reduces to nearly zero. The thermal bow raises the high spot, which causes the rub to become more severe.

A runaway situation may occur where the rotative speed (1X) vibration grows until the machine is taken off-line by a vibration limit or by some other means, or the machine is destroyed. There are many known cases where the machine destroys itself in about 2 to 20 minutes. There is NO phase lead or lag of the 1X in this failure mechanism. It is amplitude increase only.

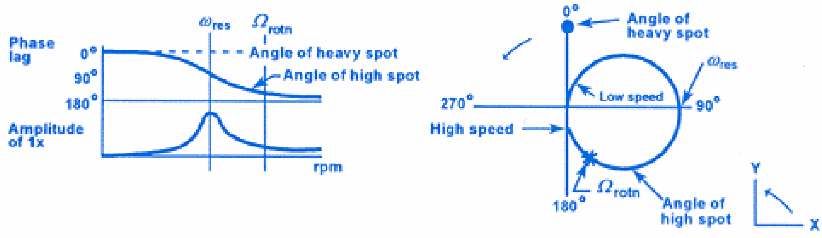

Figure 3

The brilliant mechanical engineer, Jacob Den Hartog, once told me about a consulting job he did (for Exxon, as I recall). An electric motor had suffered such a failure, and while he was pondering the cause of the problem, he leaned against the end of the machine. Its 1X vibration immediately climbed. He stopped leaning against the end, and the vibration went down. He said, "I then asked the plant engineer for the motor drawings. These drawings showed a 45 degree taper on the shaft, and a 45 degree taper on the end cover." He then observed that, if the end cover is pushed, the rub would occur. Since this motor was operated well below its mechanical resonance, the "runaway" thermal bow would occur. Professor Den Hartog really enjoyed this extremely simple problem.

The lagging 1X phase angle due to a light thermal rub that "everyone knows" is closely related to the above noted catastrophic example. However, in this phase lagging case, rotative speed is below resonance. For a typical example, assume that this high spot lags the heavy spot by approximately 20 degrees. Now, as the rotor heats at the high spot, the

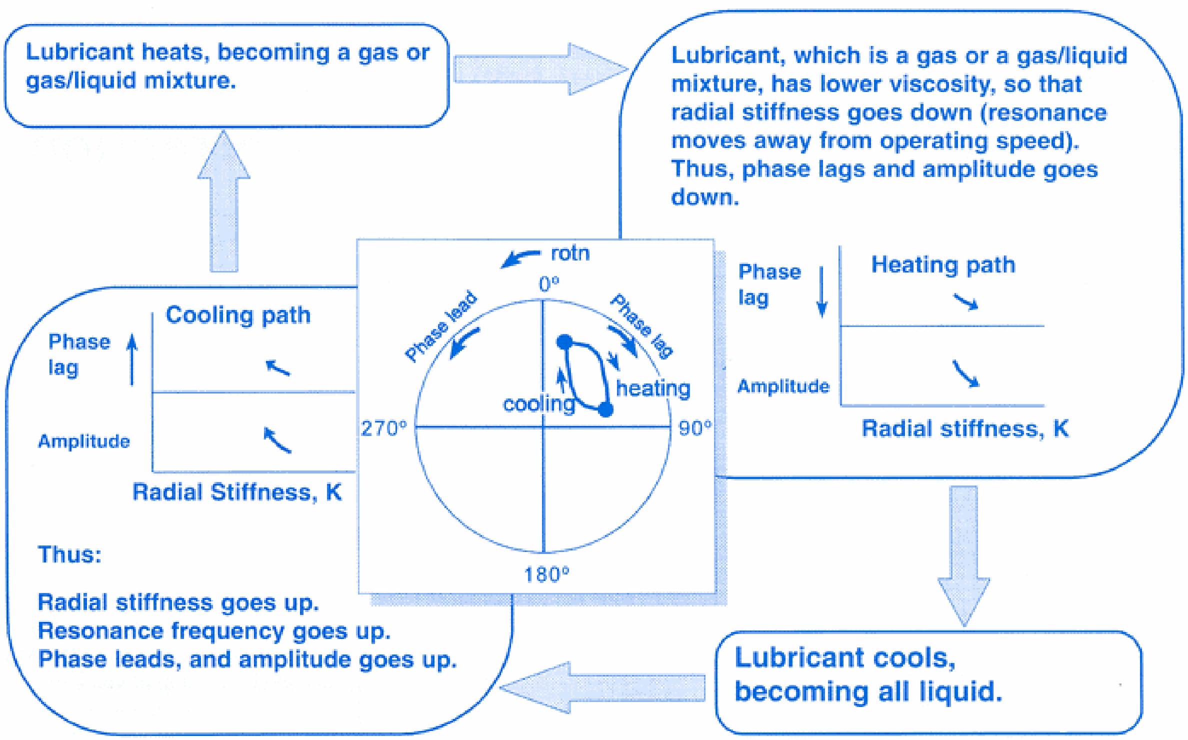

Figure 4
Cyclic behavior of rub with condition of operating speed just above mechanical resonance.

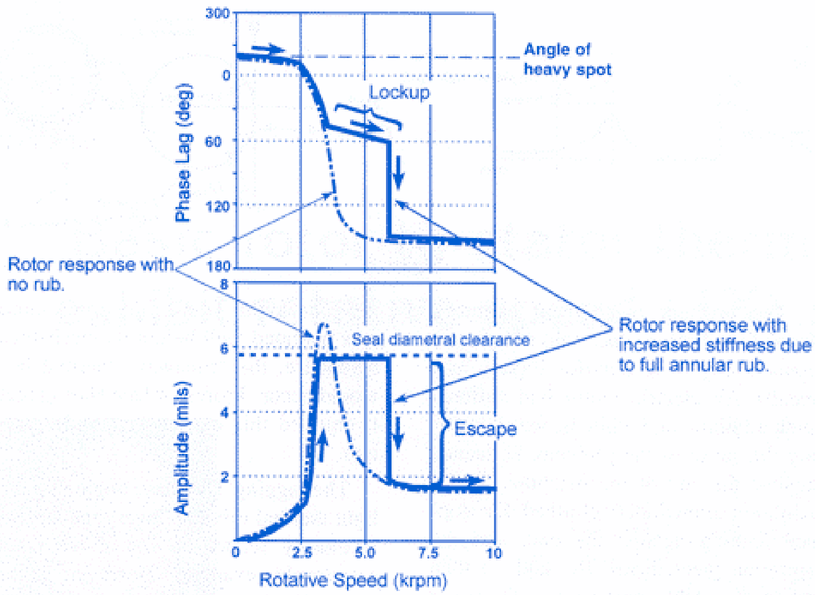

Figure 5
Full annular synchronous rub.

heavy spot moves toward the high spot, and the 1X phase continues to lag as a function of time.

The three possible situations are:

1) The rotor continuously phase lags, and amplitude is nearly constant.

2) The phase lag occurs and the amplitude decreases, and the rotor is released from the rub.

3) The rotor phase lags, and the amplitude spirals out until destruction (about the same as the first example).

The 1X phase leads rub

For many years, I have noted that if there was a mechanical balance resonance well below rotative speed, as in the Figure 3 Bode plot and polar plot, the machine would correct itself. Assume that the high spot is lagging the heavy spot by 170 degrees. Then, as the high spot heats, the shaft bows toward that high spot and, since that is nearly opposite the heavy spot, compensates for it. This self-correction is a sort of oxymoron situation. Since it self-corrects, it escapes observation (so far).

There are several case histories of rubs which generate phase lead of rotative speed that are not yet well explained. Figure 4 shows an unusual mechanism that succeeds in doing phase lead. As is described in Figure 4, the operating speed is just above a system mechanical resonance (critical), and the bearing stiffness changes, as a function of the amplitude of rotative speed. Bearing and seal direct stiffness terms are very directly dependent on lubricant viscosity. The lubricant is at its boiling point for its pressure, so it can easily move from liquid to gas. As this system cycles, the thermal delays create the phase lead characteristics. It is interesting that such a cycle may come to rest at either end of the cycle. Cycle time is, therefore, not only variable from a few minutes to nearly an hour, and the cycle is also interruptible.

There is another type of rub with a rotative speed symptom which we have previously published that is important because of its large number of occurrences.

As a reminder and comparison, this rub occurs as a full circular stator contact of the rotor when a shaft bow, such as due to unbalance, occurs. When the rotative speed is increased, the unbalance creates enough force to cause the rotor to contact the rub spot before the resonance hump "critical."

As may be seen in Figure 5, the rotor gets "stuck" on top of its "critical." The phase lag is usually about 80 to 100 degrees. As speed increases, the rub increases, so the direct dynamic stiffness increases. This raises the "critical," thus establishing this "lockup" situation. Probably, there are millions of multi-stage vertical pumps that spend their entire lifetime in this condition. Notice that, if the rotative speed is well above the nameplate "critical," a lucky impact on the shaft can remove the continuous rub situation, and the machine operates at much higher efficiency.

For field balancing, note that the synchronous rub can introduce somewhat abnormal influence vectors to normal when, and if, the balancing procedure relieves the rub.

Summary

This is a brief view of some popular thermal-induced rotative speed rubs. There are many more rub mechanisms and, of course, a lot more symptoms.■

Correction

The June 1996 issue of Orbit contained three errors in the equations in "Margin of Stability." The errors appear on page 5 in the equations that describe Figures 1(a) and 1(c). The double dashes in those equations are incorrect; they should be minus signs. The equations in Figure 1 should read:

$K - M\omega^2 + j1872.5$
$297.75 + jD(\omega - \lambda\Omega)$
and
$K - M\omega^2 + jD(\omega - \lambda\Omega)1872.5$

A corrected version of the article can be found on the Internet at http://www.bently.com. If you would like us to mail you a revised copy, please fax the Orbit editor at (702) 782-9337 or call (702) 782-3611 ext. 9493.■